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A STUDY OF THE MINIMIZATION OF THE ADVERSE EFFECTS OF CHROME PLATING ON THE FATIGUE LIFE OF AISI 4340 STEEL AND THE CORRELATION OF FATIGUE AND ELASTIC LIMITS

NAVAL AIR MATERIAL CENTER
PHILADELPHIA, PENNSYLVANIA

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P H I L A D E L P H I A, P E N N S Y L V A N I A

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PHILADELPHIA 12, PENNSYLVANIA

AERONAUTICAL MATERIALS LABORATORY

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A STUDY OF THE MINIMIZATION
OF THE ADVERSE EFFECTS OF CHROME
PLATING ON THE FATIGUE LIFE OF AISI 4340
STEEL AND THE CORRELATION OF FATIGUE AND ELASTIC LIMITS

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ABSTRACT

The effect of shot-peening prior to and baking after chrome plating AISI 4340 steel was investigated at strength levels up to 295,000 psi. It was found that this treatment had excellent beneficial effects on the fatigue limits of chrome plated 4340 steel at all the strength levels likely to be used in aircraft construction.

It was determined that there was no relationship between the fatigue limits and any of the other mechanical properties of the plated steel. In the case of the unplated steel, it was established that there was a definite straight-line functional correlation between the fatigue limit to elastic limit ratios and the tensile strength levels of the steel.

I. INTRODUCTION

1. To meet the strength requirements of some materials applications in the aircraft industry, efforts have been made to utilize the potential advantage of the relatively high strength-weight ratio of alloy steels by heat treatment to strength levels above 200,000 psi, and more nearly approaching 300,000 psi. However, increasing the strength of important steel component aircraft structures beyond the customary upper limit of 200,000 psi has introduced problems of hydrogen embrittlement and reduced fatigue life, whenever such high-strength steel parts have been chrome plated by the standard electroplating practices. The basic objective of this project, authorized by reference (a), was to determine certain specific effects of plating on high tensile strength steels which affect the serviceability of aircraft parts.

2. Available data on steels of lower strength indicate that shot-peening prior to plating will reduce the extent of fatigue damage caused by chrome plating, and that baking will somewhat reduce the embrittlement effects of hydrogen. Accordingly, Chromium Plating Specification QQ-C-320 has been amended to require that steel parts, Rockwell C40 hardness and above, which are critical in fatigue, shall be shot-peened prior to and baked after chrome plating, to develop optimum strength characteristics in plated high-strength steel parts.

3. It was not known, however, at what strength level above 220,000 psi the new requirement in the specification would insure avoidance of serious embrittlement effects and fatigue damage. The purpose of this facet of the project, authorized by reference (b), was to determine what quantitative effects shot-peening prior to and baking after chrome plating had on the fatigue limits of AISI 4340 steel, heat treated to strength levels up to 295,000 psi.

4. Reference (b) further suggested that there might be a possible correlation between the elastic strength, as measured by the repeated load method, and the fatigue limit. As an additional facet of this project, then, a rather cursory investigation was conducted to determine whether there might be a significant correlation between the elastic strength and the fatigue limit of plated and unplated 4340 steel of different strength levels.

II. SUMMARY OF RESULTS

1. It was quantitatively determined that chrome plating had a deleterious effect on the fatigue limits of the 4340 steel, ranging from a reduction of between 55% and 22% of the fatigue limits of the basis metal. The amount of fatigue damage varied with the strength level, being greatest at the lower strength level, less at the intermediate strength levels, and increased again at the highest strength level. However, it was found that shot-

peening prior to and baking after chrome plating had excellent beneficial effects on the fatigue limits of this steel at all the strength levels likely to be encountered in aircraft construction. Shot-peening and baking increased the fatigue limits of the plated specimens to values that exceeded those of the base metal, and increased the finite life to an even greater extent.

2. There proved to be a definite linear relationship between the fatigue limit to elastic limit ratios of the unplated steel and the tensile strength levels investigated, but no other relationship to any of the other mechanical properties was ascertained. In the case of the plated steel, no correlation at all was obtained between the fatigue and elastic limits or any of the other mechanical properties.

III. CONCLUSIONS

1. The results of this investigation clearly emphasize the beneficial effects that may be derived by shot-peening prior to chrome plating and subsequent baking of chrome plated high strength 4340 steel parts in overcoming loss in fatigue strength due to the plating. From this, it may be concluded that all chrome plated high strength steel parts, which are used in applications where high fatigue strength or unlimited life are design criteria, should be shot-peened prior to and baked after chrome plating.

2. It was ascertained that there was a linear correlation between the ratios of the fatigue limit to the elastic limit and the tensile strength levels of the unplated 4340 steel. There were no other relationships revealed between the fatigue limits and any of the other mechanical properties of either the plated or unplated steel

IV. RECOMMENDATIONS

1. It is strongly recommended that there be strict adherence to the requirements of Amendment I of Chromium Plating Specification QQ-C-320 that plated parts which have a hardness of Rockwell C40, or above, which are designed for unlimited life under dynamic loads, be shot-peened prior to plating and baked after plating.

2. It is recommended that additional studies be initiated in the following areas to supplement the limited work done and reported herein:

a. A comprehensive study of the relationship of the fatigue and elastic limits of a variety of steels at different tensile strength levels;

b. The probable beneficial effect of "coaxing" on the fatigue properties of chrome plated steels;

c. The effect of shot-peening after plating on the fatigue properties of chrome plated high strength steels.

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DESCRIPTION OF TEST - ANALYSIS OF RESULTS

Description and Test Method

1. The material used was from a commercial heat of AISI 4340 steel in accordance with MIL-S-5000A, meeting the requirements shown below:

Carbon	.38/.43
Manganese	.60/.80
Phosphorus	.040 Max.
Sulphur	.040 Max.
Silicon	.20/.35
Nickel	1.65/2.0
Chromium	.70/.90
Molybdenum	.20/.30

2. The steel was normalized at 1600°F for 30 minutes, austenitized at 1525°F for one hour, oil quenched, and then tempered for one hour at the temperatures shown below for the corresponding strength levels.

Strength Levels/ksi	Tempering Temperatures
175-185	1000°F
230-240	735°F
250-260	630°F
285-300	400°F

3. Shot-peened specimens were peened in an airless blast machine, using S-110 heat-treated steel shot to produce a uniform coverage having an arc height of A2-.009" to .010". 4000 rpm 108 rpm 5 min.

4. Specimens were chrome plated at a current density of 2 amperes/square inch for two hours. The ratio of chromic acid to sulphate in the chromium plating bath was 100 to 1; 33 ounces of chromic acid to the gallon was used. The bath temperature was maintained at 131°F ± 1°, with air agitation. These plating conditions resulted in a plating thickness of 0.002", with a tolerance of -0.0005" + 0.

5. Baking of specimens consisted of heating at 375°F ± 25° for 3-1/2 hours. The fatigue evaluation was performed using standard rotating beam type fatigue machines. The usual operating procedures were followed of subjecting specimens to successively lower values of stress and determining the number of cycles to failure, until a stress level was reached at which the specimens did not fracture in a given number of cycles, 20 million cycles in this investigation. Control specimens were ground and highly polished.

6. The fatigue evaluation consisted of establishing S-N curves for steels heat treated to obtain four different strength levels, each strength level involving curves for each of six groups, as follows:

1. Control - basis metal
2. Chrome plated
3. Chrome plated and baked
4. Shot-peened
5. Shot-peened and chrome plated
6. Shot-peened, chrome plated and baked

7. In connection with the fatigue evaluation, rather brief and preliminary investigations were made of the following areas of interest:

a. S-N curve of machined specimens compared to that of ground specimens, both groups highly polished;

b. Effect of shot-peening after plating on the fatigue properties of chrome plated steel;

c. Effect of "coaxing" unpeened chrome plated specimens on the fatigue properties.

8. The elastic limits of the different strength level steels were determined using standard .505" tensile specimens which were initially highly polished. Using standard techniques, two Baldwin SR-4 strain gages, Type A-3, were attached on opposite sides of the gage length of each specimen. The strain gages were connected in series to give average readings. A duplicate unstressed specimen with strain gages was utilized to provide temperature compensation. As the tests progressed, it was observed that there was considerable slippage of the strain gages with application of high loads. This was attributed to the high degree of polish on the gage section of the specimens. It was found that if the surfaces of the highly polished specimens were roughened slightly by vapor blasting prior to the attachment of the gages, the gage slippage was completely eliminated.

9. Values of the elastic limit are, of course, arbitrary in nature and depend upon the magnitude of the permanent set established as a standard, of which there seems to be a great lack of uniformity. Values of the elastic limits vary greatly with the sensitivity and accuracy of the testing and strain measuring equipment, eccentricity of loading and other factors. For the purpose of this evaluation, the requirements of the Federal Test Method Standard No. 151 were used as a criteria for the determination of the elastic limit, which is defined therein as the maximum stress which causes a permanent set equal to or greater than 0.000030 inch per inch of gage length upon complete release of load.

10. A predetermined load of approximately 20% of the expected elastic limit was applied several times to condition the strain gages, which stabilized the operation and reduced the tendency of the gages to fail to return to the initial zero after removal of the first load. In making

strain measurements, the initial and final strain readings after removal of test load were taken using a small load of about 200 lbs., instead of zero load. Strain readings were recorded at load and after removal of load, by balancing the strain indicator. Cycles of loading were repeated with successively higher loads in increments of 5000 lbs., until a slight set was observed, and then loading proceeded in small increments of 1000 lbs., and later 500 lbs., as the elastic limit was approached.

11. After the elastic limit determinations were made, the SR-4 strain gages were removed from the specimens and the usual engineering tensile data were obtained using the standard autographic methods.

Analysis of Results

A. Minimization of the Adverse Effects of Chrome Plating on the Fatigue Life

1. For the purpose of discussion, the different strength levels were qualitatively classified on the basis of the average of the strengths of three tensile specimens of the unplated steel. On this basis, the results of the fatigue evaluations are shown graphically on Plates 1 to 4, inclusive, for the 180 ksi, 235 ksi, 255 ksi and 295 ksi strength levels, respectively. The usual amount of fatigue scatter was obtained, but in the interest of clarity, the individual test plots are not shown on the graphs. The detailed evaluation test results are listed in tabular form in Appendix 1, Tables 1 to 4, inclusive, for the 180 ksi, 235 ksi, 255 ksi, and 295 ksi strength levels, respectively.

2. On Plate 5 are shown the relative values of the fatigue limits obtained for the various groups of specimens, as affected by the different surface treatments. The fatigue limits, based on 20 million cycles of repeated stress, are summarized below, for each strength level, together with a comparison of the value of the fatigue limit of each group to its control:

Fatigue Limits

Strength Level, ksi	180		235		255		295	
	ksi	%	ksi	%	ksi	%	ksi	%
Control	84	100.0	98	100.0	98	100.0	97	100.0
Plated	38	45.2	76	77.6	77	78.6	48	49.5
Plated and baked	59	70.0	79	80.6	76	77.6	48	49.5
Shot-peened	91	108.3	101	103.1	102	104.1	98	101.0
Shot-peened and plated	82	97.6	102	104.1	97	99.0	90	91.8
Shot-peened, plated and baked	95	113.1	103	105.1	99	101.0	100	103.1

3. In similar fashion, the values of the fatigue strength at 100,000 cycles are shown in graphical form on Plate 6 and are summarized below for each strength level, together with a comparison of the values of the fatigue strength of each group to its control:

Strength Level, ksi	Fatigue Strengths 180 ksi	180 %	235 ksi	235 %	255 ksi	255 %	295 ksi	295 %
Control	109	100	117	100	125	100	133	100
Plated	70	64.2	94	80.3	95	76.0	72	54.1
Plated and Baked	82	75.2	100	85.5	89	71.2	76	57.1
Shot-peened	115	105.5	133	113.7	135	108.0	155	116.5
Shot-peened and plated	104	95.4	120	102.6	132	105.6	135	101.5
Shot-peened, plated and baked	112	102.8	130	111.1	141	112.8	139	104.5

4. From an examination of the tabulated and graphical presentation of the data, the following conclusions may be deduced concerning the effects of the various treatments on the fatigue limits of 4340 steel at different strength levels.

a. Fatigue limit values of the base metal increased with ultimate strength up to a certain point and then leveled off. Other investigators have in fact, found that at the higher strength levels, the fatigue limits actually decrease with increased tensile strength. This would indicate that there is nothing to be gained in going to an extremely high strength level solely in attempts to obtain increased fatigue limits for the base metal. However, in the event that structures, such as aircraft landing gears, are designed on the basis of static strength, then it would be advantageous to go to a higher strength level since the fatigue limit would be somewhat equivalent to that of the same structure designed on the basis of a lower static strength.

b. It was quantitatively determined that chrome plating has a deleterious effect on the fatigue life of steel, the amount of damage depending upon the strength level of the steel. It was found that the percentage of reduction in fatigue limit was greatest at the lower strength level, not as great at the intermediate strength levels, and increased again at the higher strength level.

c. Baking after plating had considerable beneficial effects at the lower strength level, but its effects were negligible at the higher strength levels, although in no case were any harmful effects noted as a result of baking.

d. Shot-peening increased the fatigue limits of the base metal in all cases, the amount depending upon the strength level of the steel, a greater improvement occurring at the lower strength. Since shot-peening improvements are a result of the combination of cold working and the inducing of compressive residual stresses on the surface, the greater beneficial effects at the lower strength level are probably due to the greater susceptibility of the lower strength steel to cold working. Even though the increase in fatigue limits of the base metal at some strength levels was slight, as a result of shot-peening, in all cases, the increase in finite life was considerable.

e. Shot-peening prior to plating was extremely beneficial, at times even increasing the fatigue limits of plated specimens to values above those of the basis metal, and increasing the finite life to an even greater proportional extent.

f. Baking specimens (after plating) that had been shot-peened prior to plating was beneficial in all cases, to the extent that specimens undergoing shot-peening prior to and baking after plating had fatigue limits that exceeded those of the base metal.

To summarize the results of this phase of the investigation, it was found that shot-peening prior to and baking after chrome plating had excellent beneficial effects on the fatigue limits of 4340 steel at all the strength levels likely to be used in aircraft construction. The findings of this investigation offer significant evidence to substantiate the requirement of Amendment 1 of Specification QQ-C-320 that all chrome plated steels which are designed for unlimited life under dynamic loads be shot-peened prior to and baked after chrome plating.

5. An economical and unique method of fabricating rotating beam fatigue specimens had been developed at the Aeronautical Materials Laboratory which involved grinding of specimens. It was considered desirable to continue to use this rapid fabricating technique in the evaluation of the effects of shot-peening and baking on the fatigue properties of the 4340 steel studied in this investigation. However, it had been reported by an airframe manufacturer that grinding had an adverse effect on the fatigue properties of high strength steels. In order to confirm this, a group of machined specimens at the 285-300 ksi strength level was checked against a group of ground specimens and the results, shown in Table 4, indicate a slight superiority of 1000 psi in the fatigue limit of the machined specimens, a difference well within the scope of experimental error.

6. It is believed that reduction in fatigue limit in the grinding of high strength steel parts may have been simply due to unfavorable grinding conditions; that is, improper abrasive, heavy grinding cuts, unsuitable coolants, etc. Under controlled laboratory conditions, using proper abrasive, coolant and taking light grinding cuts, such as were utilized

in this investigation, it was found that there was no significant difference in the fatigue properties of the ground and machined steel specimens.

7. Instances have been reported in some of the literature where shot-peening specimens after, instead of before plating had greatly increased the fatigue life of nickel plated steels. In consideration of this possibility occurring with chrome plating, two groups of specimens at the 295 ksi strength level were shot-peened after chrome plating and fatigue tested. The detailed test results are listed in Table 5, and shown graphically on Plate 7 together with curves of specimens peened before plating. A summary and comparison of the effects of shot-peening before and after plating and subsequent baking is shown below:

Condition	Fatigue Limit/ksi	% Control
Control	97	100
Shot-peened and plated	90	92.8
Shot-peened, plated and baked	100	103.1
Plated and shot-peened	99	102.1
Plated, shot-peened and baked	102	105.2

Thus, the fatigue limit of specimens peened after plating proved to be about 10% greater than that of specimens peened before plating. In order to determine what effects, if any, shot-peening after plating had on the corrosion resistant properties of the chrome plated steel, a number of each type of broken fatigue specimens were subjected to salt-spray corrosion tests. It was observed that the least corroded of the specimens tested were those peened after plating, these specimens having less than 20% of the surface corroded in 115 hours. Specimens revealing maximum effect of corrosion were those shot-peened before plating, these specimens showing 40 to 60% of the surface corroded after 1 hour and 60 to 100% corroded after 115 hours. A detailed chart of the effects of surface treatments on the corrosion resistant properties of these specimens is shown in Table 6 and are summarized below in a descending order of merit:

1. Plated and Peened
2. Plated, Peened and Baked
3. Plated and Baked
4. Plated only
5. Peened, Plated and Baked
6. Peened and Plated

8. In addition, microscopic examinations were made of several of the specimens to determine what physical effects shot-peening after plating had on the chrome plating itself. There seemed to be very little difference between the appearance of the chromium coatings of the specimens shot-peened before or after plating. Peening after plating would have a tendency to minimize the stress concentration effects by rounding off the many macroscopic cracks that are present on the surface of an electrodeposited hard

chromium plate. Peening would appear to place the surface of the plating in a state of compressive residual stress, both changes being conducive to improved fatigue properties. For the same reasons, improved corrosion resistance and stress corrosion resistance could be expected from the specimens peened after plating.

9. From this limited investigation, it would seem that consideration could be given to the possibility of shot-peening parts in service that had been susceptible to fatigue failure because of reduced fatigue properties due to chrome plating. Such parts could be removed, shot-peened (without stripping the plating) and re-installed with a minimum of inconvenience. Where rubbing surfaces are factors, these surfaces could be smoothed by the honing process which treatment in itself is conducive to improved fatigue properties.

10. It is a well known fact that remarkable increases in the fatigue strengths and fatigue limits of virgin steel may be obtained by the "coaxing process." The "coaxing process" involves repeated understressing for 10 million cycles at a level just below the fatigue limit, followed by a few million cycles at each of a series of higher stresses, increased in gradual steps. However, no work on the effect of the "coaxing process" on the fatigue properties of chrome plated steel is known to have been published. In order to obtain some data which would be of academic interest and possible future practical use, a number of chrome plated specimens were subjected to the "coaxing process". This was done in a random and very restricted fashion, since the number of specimens for the basic project itself was initially limited. Specimens that proved to have unlimited life were subjected to increasing stress in increments of 3000 psi and run for 5 million cycles at each stress level until fracture occurred. The highest stress sustained by the specimens without fracture was defined as the new coaxed fatigue limit. Rather interesting results were obtained as follows:

Fatigue Limits, Unplated Steel

	Virgin	Shot-Peened		Coaxed*	
Strength Level/ksi	ksi	ksi	% Inc.	ksi	% Inc.
[illegible]	84	91	8.3	93	10.7
235	98	101	3.1	100	2.0
255	98	102	4.1	103	5.1
295	97	98	1.0	107	10.3

Fatigue Limits, Plated Steel

	Virgin	Shot-Peened		Coaxed*	
Strength Level/ksi	ksi	ksi	% Inc.	ksi	% Inc.
180	38	82	115.8	56	47.3
235	76	102	34.2	81	6.6
255	77	97	26.0	86	11.7
295	48	90	87.5	77	60.4

*Average of 2 specimens

Correlation of Fatigue and Elastic Limits

1. A previous investigation conducted at the Massachusetts Institute of Technology, reference (c), indicated that there might be a significant correlation between the elastic limits, measured by the repeated load method, and the fatigue limits of some steels. If it is assumed that fatigue damage occurs when minute plastic deformation takes place, it would seem reasonable that fatigue limits and elastic limits might be related, since the elastic limits obtained by repeated loading were also determined on the basis of minute plastic deformation.

2. Since a considerable amount of effort had already been expended in establishing pertinent rotating beam fatigue data on the 4340 steels, at a number of strength levels, an attempt was made to determine whether a correlation existed between the values of the fatigue limits of the bare and plated metals and their elastic limits. It was recognized that the values of the rotating beam fatigue limits (complete reversal of stress) would be lower than the direct stress fatigue limits (zero minimum to maximum) and that the latter would more nearly simulate the loading cycles used for elastic limit determinations. It was further recognized that it is quite probable that there might be a correlation variation, other than quantitative, due to the different methods of stressing; that is, the rotating beam specimens were subjected to flexure stress whereas the tensile specimens were subjected to direct stress. However, due to time and financial limitations, it was decided to forego at this time the more logical correlation evaluation between elastic limits and direct stress fatigue limits, both of which use the same type of loading in their determination.

3. In the investigation conducted at the Massachusetts Institute of Technology, previously mentioned, at times, residual negative (compressive) strains appeared after unloading at loads below the elastic limit. In such cases, the elastic limit was defined as the stress at which the residual strain continued to increase in the positive direction with repeated application and removal of the same load at which the initial small increment of strain was first observed. After considerable study, these investigators believed they were justified in adopting this as a general criterion for elastic limit determination. Although no negative strains were observed in the conduct of this evaluation at the Aeronautical Materials Laboratory, several specimens were evaluated using the method of Muir, Averbach and Cohen and reasonable agreement was obtained with the values determined by using as a standard the 0.000030 inch per inch of gage length as a permanent set criterion for the elastic limit.

4. The complete data on the mechanical properties of the various strength level steels, based on an average of three test specimens in the plated and bare conditions, are listed in detail in Table 6, and are summarized below:

Plated Metal

Strength Level/ ksi	Tensile Strength/ ksi	Yield Strength/ ksi	Proportional Limit/ksi	Elastic Limit/ ksi	Fatigue Limit/ ksi
180	181.0	175.0	155.0	147.5	38.0
235	233.2	213.5	188.5	144.7	76.0
255	258.2	230.0	196.5	142.9	77.0
295	292.8	217.6	159.5	130.0	48.0

Bare Metal

Strength Level/ ksi	Tensile Strength/ ksi	Yield Strength/ ksi	Proportional Limit/ksi	Elastic Limit/ ksi	Fatigue Limit/ ksi
180	181.8	173.5	154.2	136.7	84.0
235	236.0	215.5	197.3	147.6	98.0
255	251.2	225.1	205.4	144.2	98.0
295	296.7	221.4	161.4	137.3	97.0

5. The above data are shown graphically for the plated and bare steels in Plates 8 and 9, respectively. It is apparent from an examination of both the tabular and graphical data that there is no direct linear correlation between the fatigue limit and any one of the other mechanical properties. However, the elastic limit seems to offer the best potential as the basis for the correlation of the fatigue limit to any single mechanical property, the curve of the elastic limit more nearly coinciding with that of the fatigue limit.

6. The same data are summarized below in terms of the ratio of the values of the fatigue limits of the plated and bare steels to the values of the other mechanical properties, on a comparison basis:

	180 ksi		235 ksi		255 ksi		295 ksi	
	Bare	Plated	Bare	Plated	Bare	Plated	Bare	Plated
Ultimate Strength	.462	.210	.415	.325	.390	.298	.327	.164
Yield Strength	.484	.217	.455	.356	.435	.335	.438	.221
Proportional Limit	.545	.245	.497	.403	.477	.392	.600	.300
Elastic Limit	.614	.258	.664	.525	.680	.539	.706	.369

7. Graphically, the ratios of the fatigue limits to the other mechanical properties, for the plated and bare 4340 steels of different strength levels, is shown on Plates 10 and 11, respectively. Since this evaluation is concerned only with the possible correlation of the fatigue limits with the other mechanical properties, discussions concerning the variation of mechanical properties themselves with either hardness or tempering temperature are not pertinent at this time.

8. In the case of the plated steels, there is no evidence of any correlation between the fatigue limits and any of the other mechanical properties of the plated steels. From an examination of Plate 11, it appears as if there is a definite straight line functional correlation between the ratios of the fatigue limits to the elastic limit and the different strength levels of bare 4340 steel studied in this investigation, but no correlation is indicated with the other mechanical properties of the bare steel.

9. A simple mathematical equation may be developed to show the relationship of the ratios of the fatigue limits to the elastic limits at the various strength levels for the unplated steels, as follows:

$$R = 0.0008\ T.S. + 0.470$$

R is the ratio of the fatigue limit to the elastic limit
T.S. is the tensile strength of the steel in ksi

10. From the above, the fatigue limit for any strength level of the basis 4340 steel could be predicted, if the elastic limit were first determined by the repeated load method, as described herein. Determination of the elastic limit is relatively fast and inexpensive as compared to the standard procedure for determining the fatigue limits.

11. It must be emphasized that the scope of this investigation was exploratory in nature, and was intended merely to ascertain whether there existed some sort of correlation. By its very limitations, the investigation precluded the study of a variety of steels, the use of the more sensitive but time consuming Tuckerman gages, and the testing of large quantities of specimens for proper statistical analysis. If further investigation along these lines is contemplated, it would be desirable to examine a number of steels, using Tuckerman gages, and testing a sufficient number of specimens to give significant statistical meaning to the results.

REFERENCES

(a) BUAER ltr Aer-AE-41/175707 of 19 Dec 1952

(b) BUAER ltr Aer-AE-412/222 of 11 May 1956

(c) ASME Transactions, Volume 48, Preprint No. 9 -
Some Effects of Silicon on the Mechanical Properties of
High Strength Steels by C. H. Shik, B. L. Averbach and Morris Cohen

S-N CURVES - 180,000 PSI STRENGTH LEVEL

Condition	Fatigue Limit/psi	% Control
Control	84,000	——
Plated	38,000	45.2
Plated and Baked	59,000	70.2
Shot-Peened	91,000	108.3
Shot-Peened and Plated	82,000	97.6
Shot-Peened, Plated and Baked	95,000	113.1

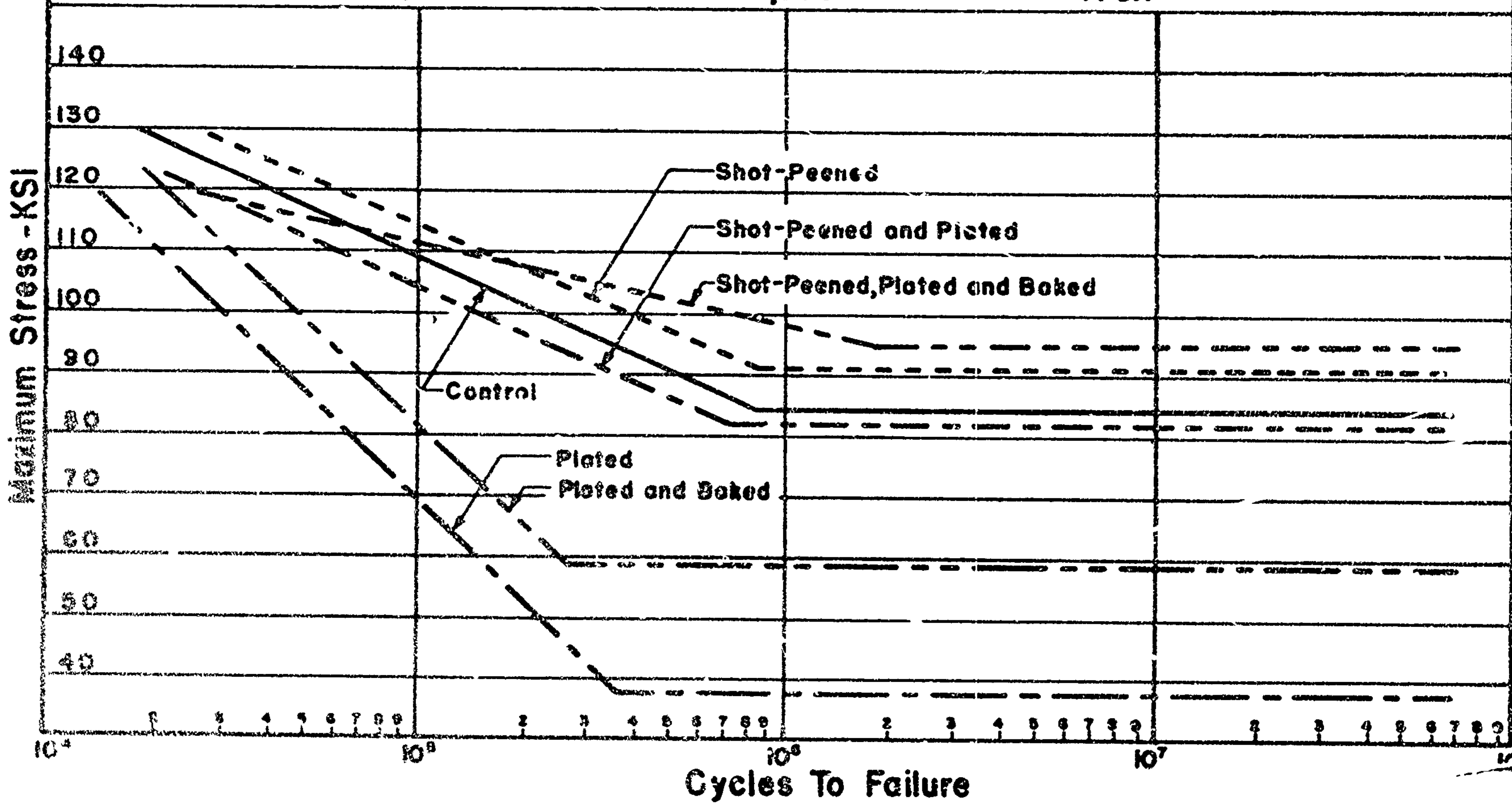
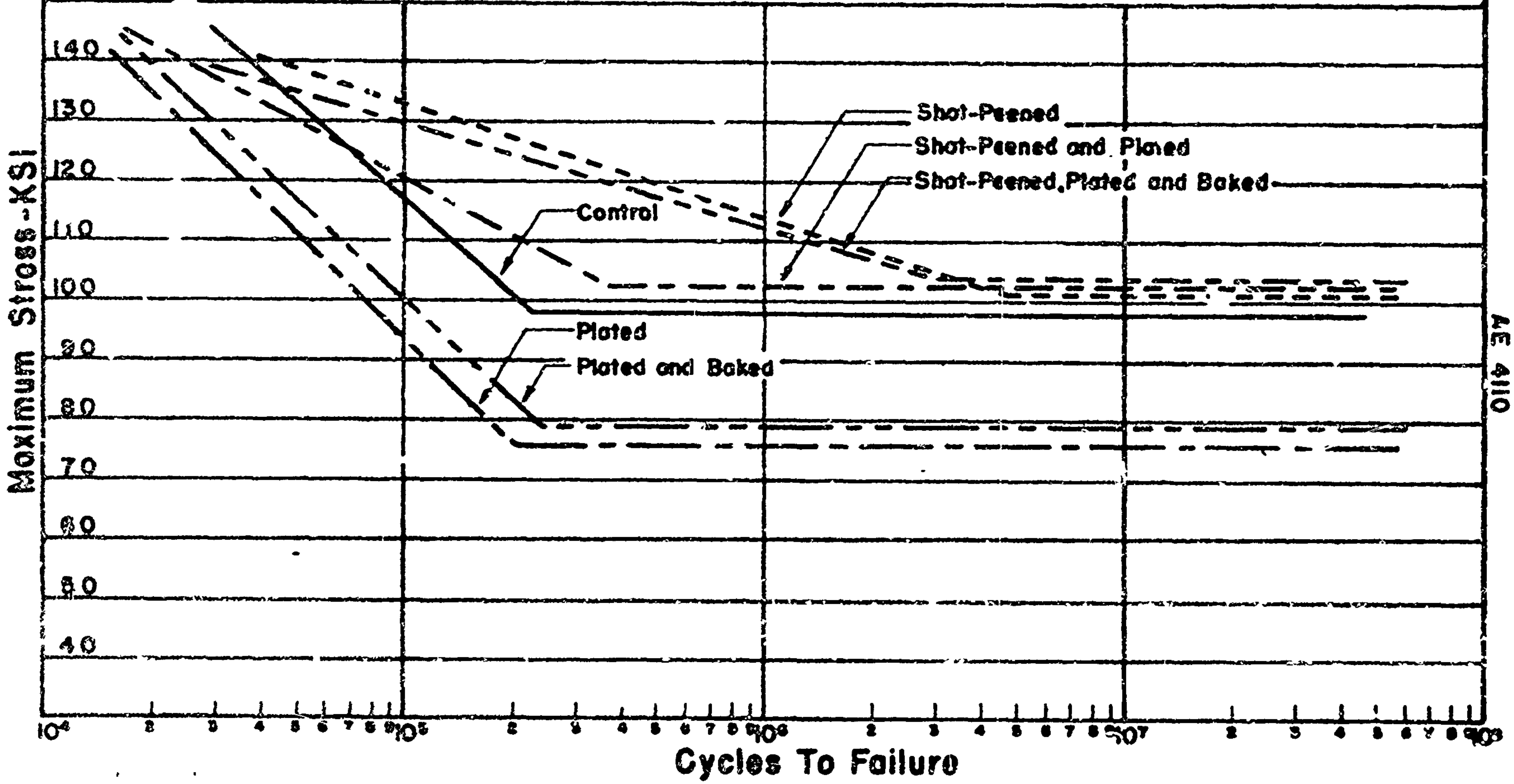


Plate I

AE 4110

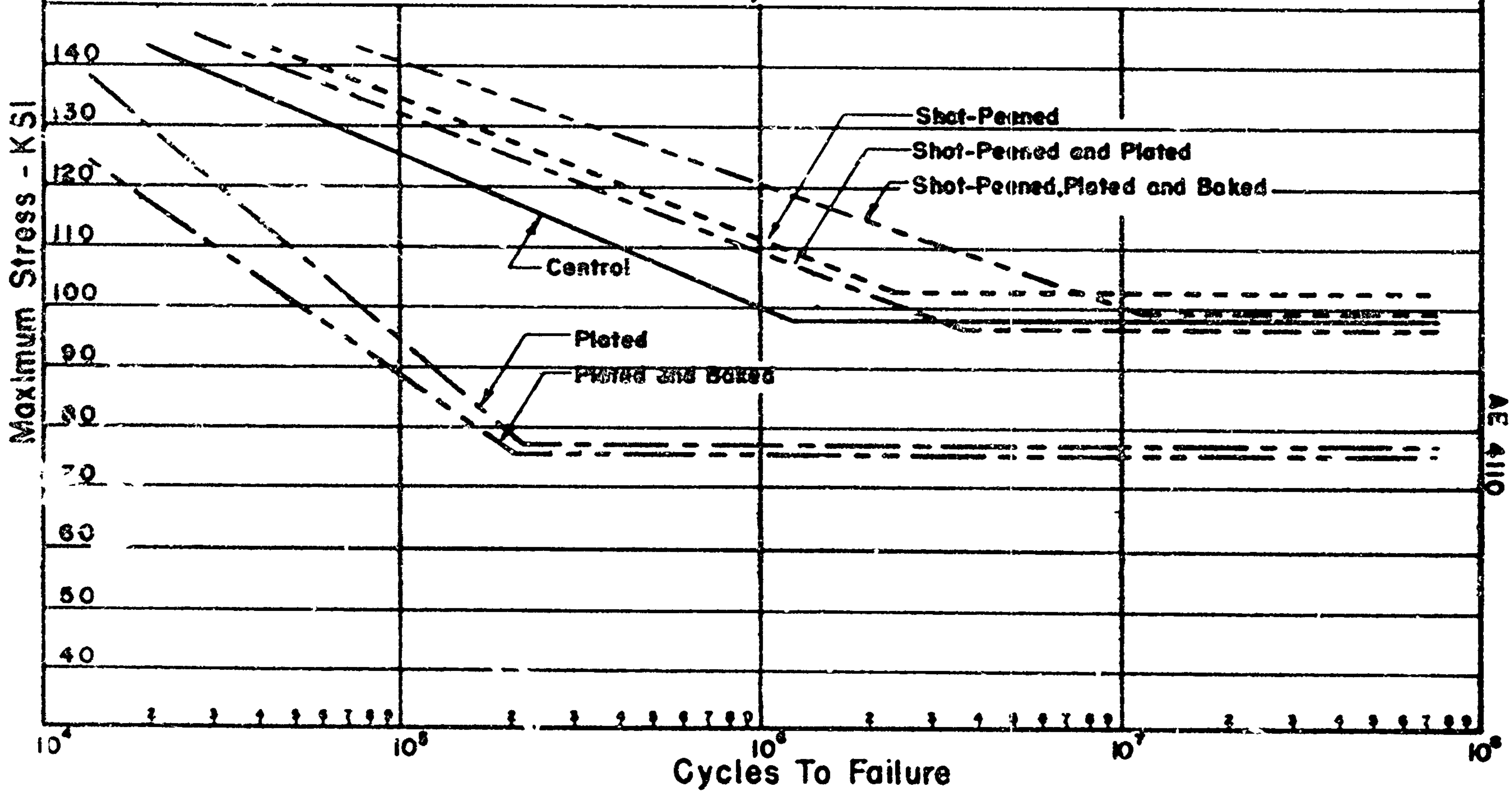
S-N CURVES-235,000 PSI STRENGTH LEVEL

Condition	Fatigue Limit/psi	% Control
Control	98,000	——
Plated	76,000	77.6
Plated and Baked	79,000	80.6
Shot-Peened	101,000	103.1
Shot-Peened and Plated	102,000	104.1
Shot-Peened, Plated and Baked	103,000	105.1



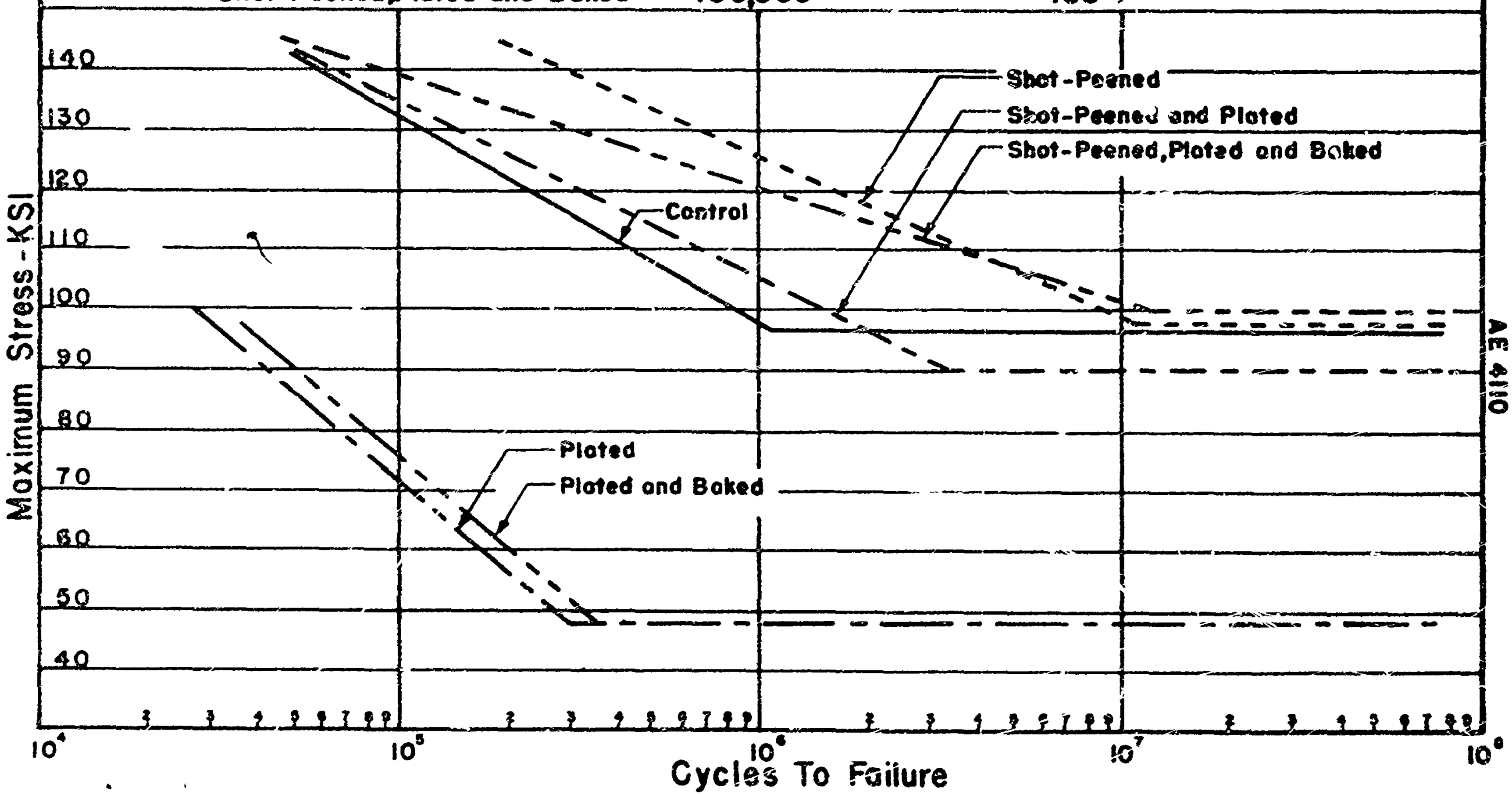
S-N CURVES-255,000 PSI STRENGTH LEVEL

Condition	Fatigue Limit/psi	% Control
Control	98,000	—
Plated	77,000	78.6
Plated and Baked	76,000	77.6
Shot-Peened	102,000	104.1
Shot-Peened and Plated	97,000	99.0
Shot-Peened, Plated and Baked	99,000	101.0



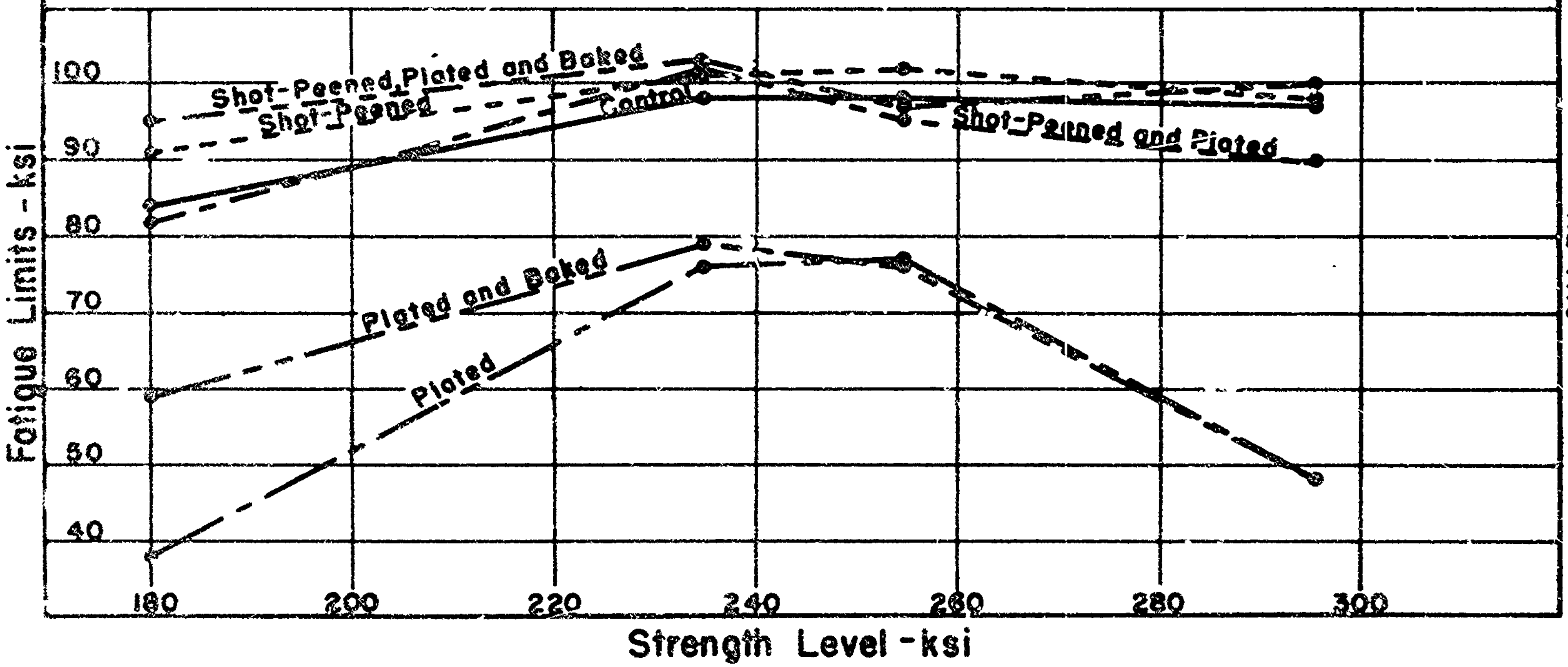
S-N CURVES-295,000 PSI STRENGTH LEVEL

Condition	Fatigue Limit/psi	% Control
Control	97,000	—
Plated	48,000	49.5
Plated and Baked	48,000	49.5
Shot-Peened	98,000	101.0
Shot-Peened and Plated	90,000	92.8
Shot-Peened, Plated and Baked	100,000	103.1



FATIGUE LIMITS

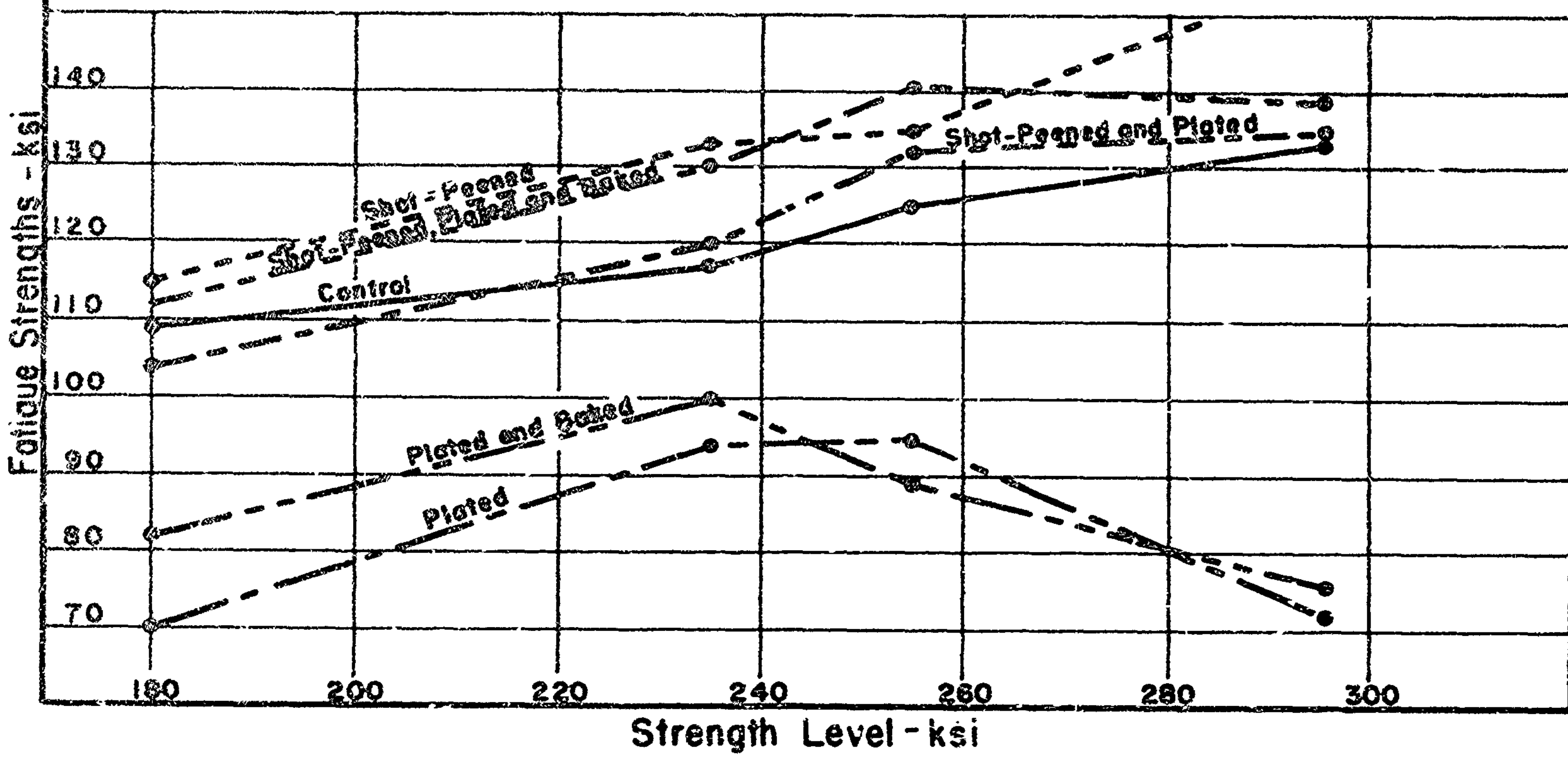
Condition	Strength Level - ksi: 180	%	235	%	255	%	295	%
Control	84	—	98	—	98	—	97	—
Plated	38	45.2	76	77.6	77	78.6	48	49.5
Plated and Baked	59	70.0	79	80.6	76	77.6	48	49.5
Shot-Peened	91	108.3	101	103.1	102	104.1	98	101.0
Shot-Peened and Plated	82	97.6	102	104.1	97	99.0	90	91.8
Shot-Peened, Plated and Baked	95	113.1	103	105.1	99	101.0	100	103.1



AE 4110

FATIGUE STRENGTHS AT 10^8 CYCLES

Condition	180	%	235	%	255	%	295	%
	Strength Level - ksi							
Control	109	—	117	—	125	—	133	—
Plated	70	64.2	94	80.3	95	76.0	72	54.1
Plated and Baked	82	75.2	100	85.5	89	71.2	76	57.1
Shot-Peened	115	105.5	133	113.7	135	108.0	155	116.5
Shot-Peened and Plated	104	95.4	120	102.6	132	105.6	135	101.5
Shot-Peened, Plated and Baked	112	102.8	130	111.1	141	112.8	139	104.5

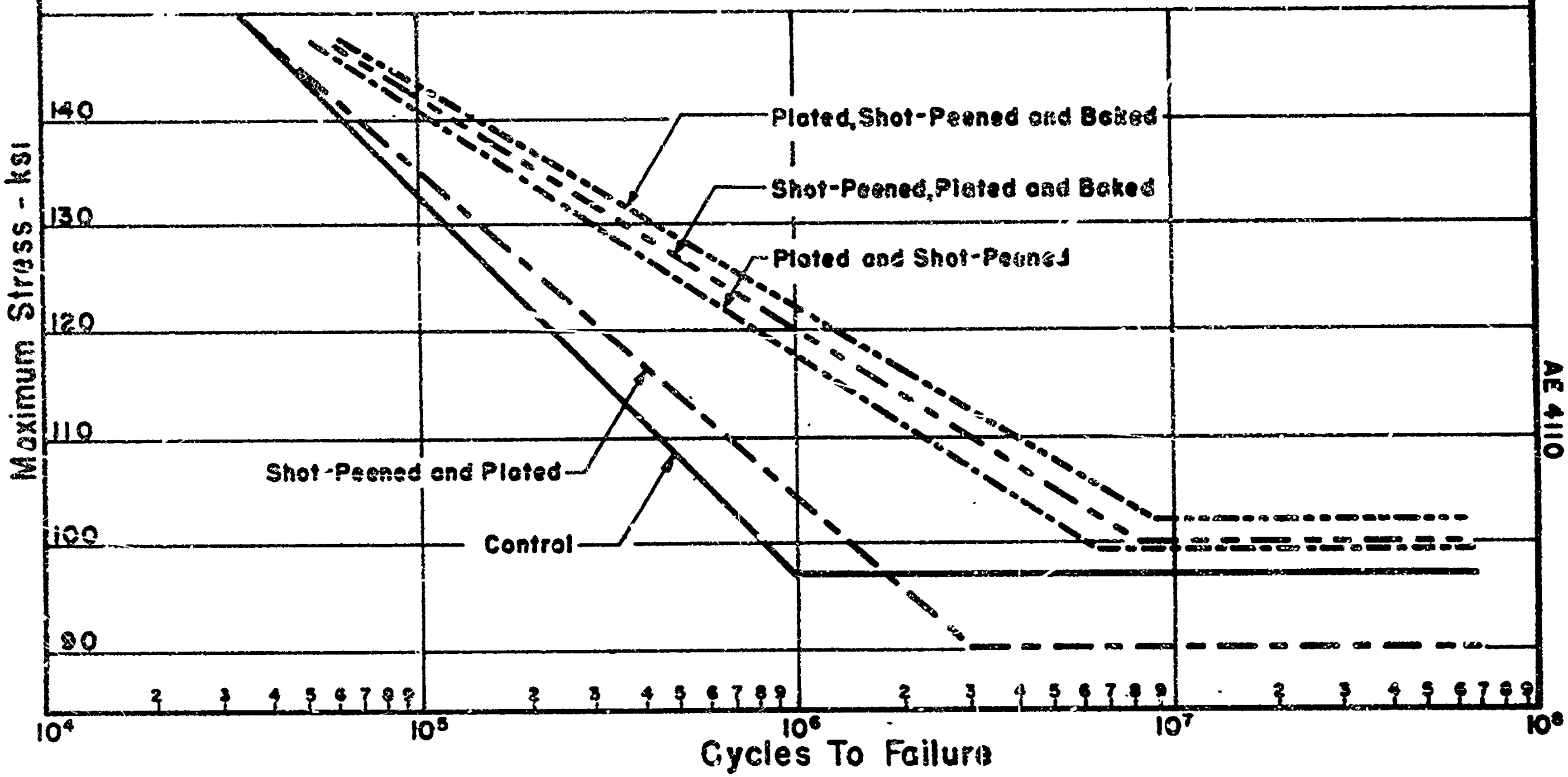


AE 4110

S-N CURVES-295,000 PSI STRENGTH LEVEL

Effects of Shot-Peening, Before and After Plating

Condition	Fatigue Limit/psi	% Control
Control	97,000	—
Shot-Peened and Plated	90,000	92.8
Shot-Peened, Plated and Baked	100,000	103.1
Plated and Shot-Peened	99,000	102.1
Plated, Shot-Peened and Baked	102,000	105.2



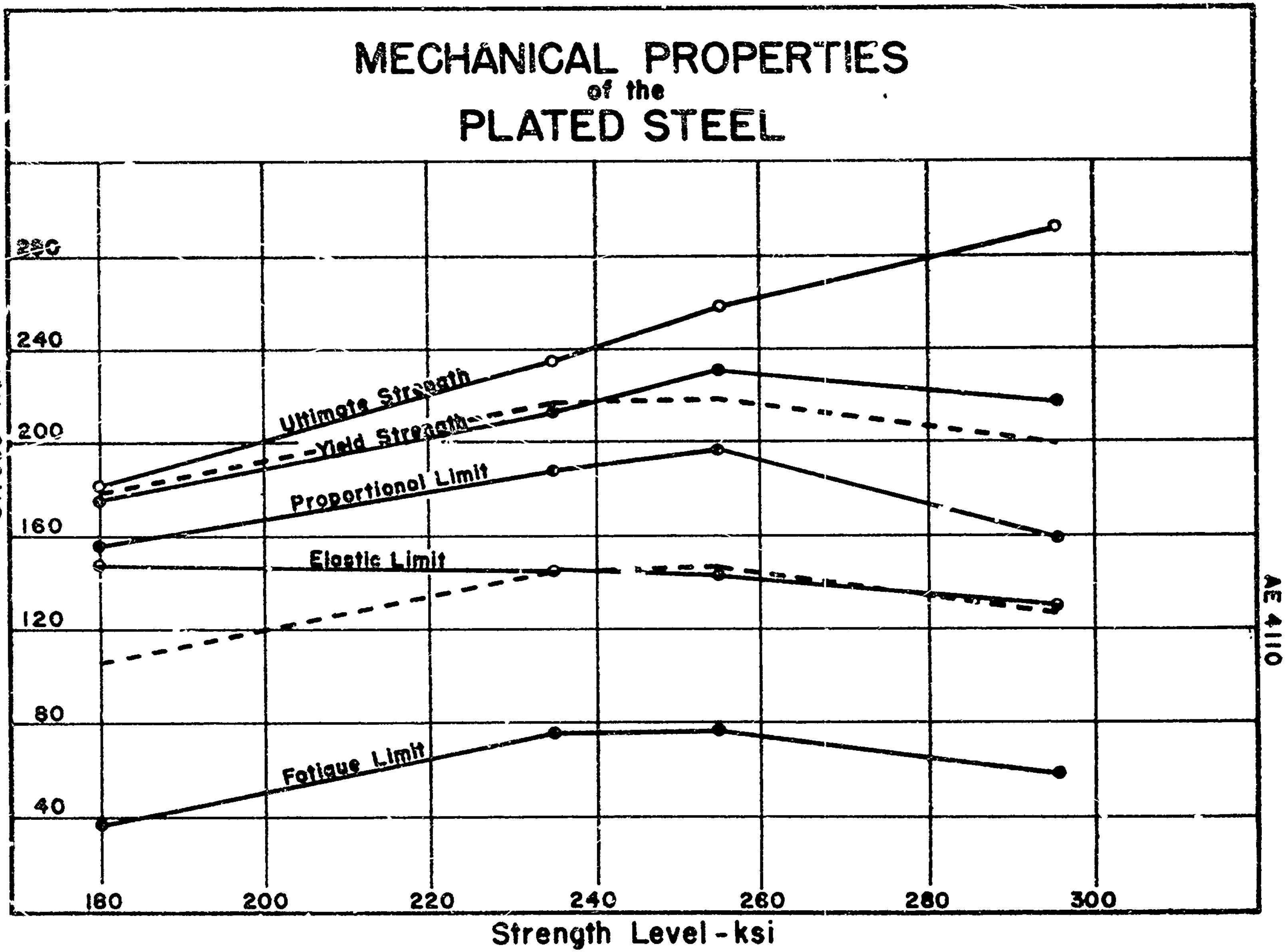

MECHANICAL PROPERTIES
of the
PLATED STEEL
Ultimate Strength
Yield Strength
Proportional Limit
Elastic Limit
Fatigue Limit
Stress - ksi
280
240
200
160
120
80
40
180
200
220
240
260
280
300
Strength Level - ksi
AE 4110

Plate 8

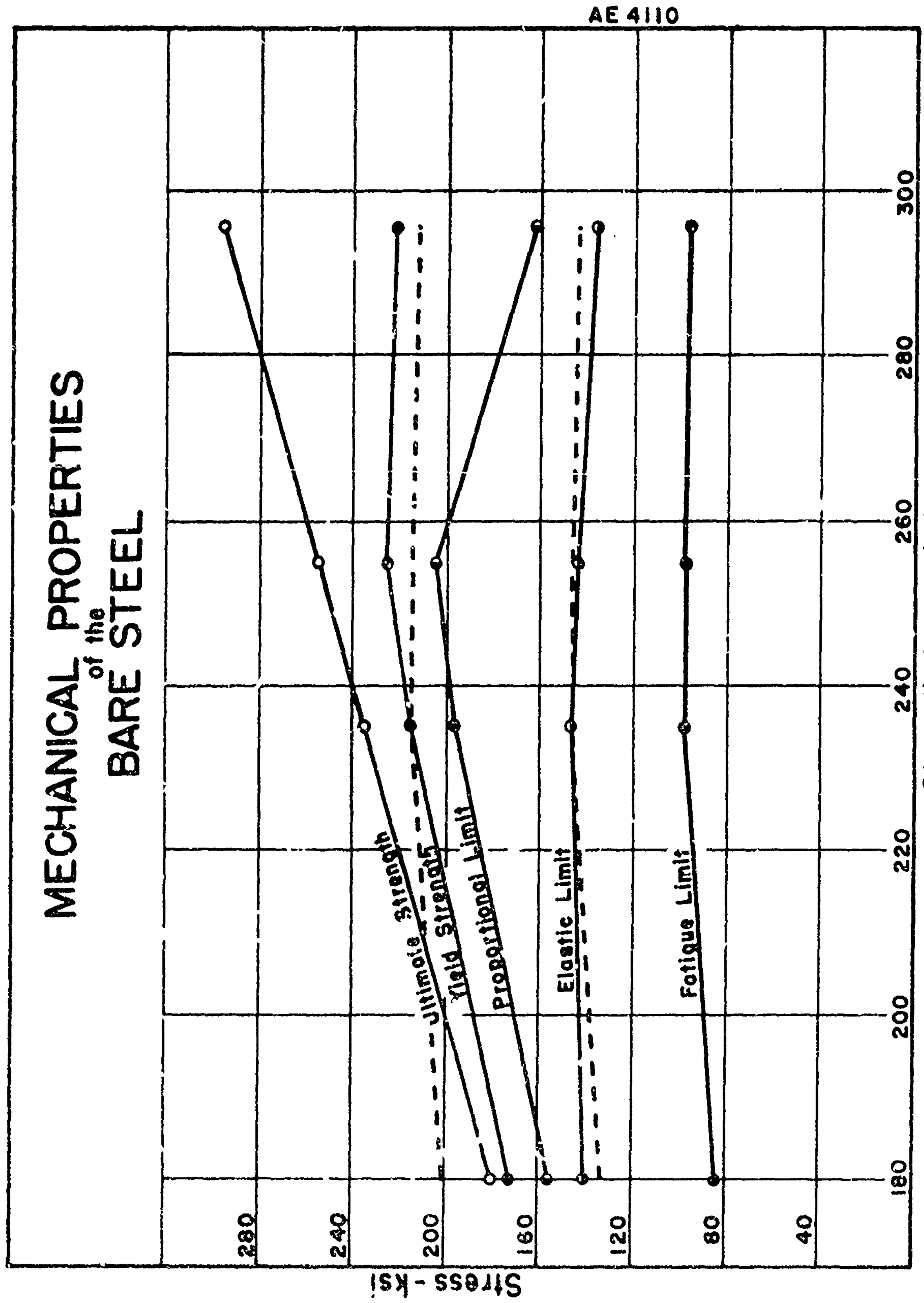

AE 4110
MECHANICAL PROPERTIES of the BARE STEEL
Ultimate Strength
Yield Strength
Proportional Limit
Elastic Limit
Fatigue Limit
Strength Level - ksi
180
200
220
240
260
280
300
Stress - ksi
40
80
120
160
200
240
280

Plate 9

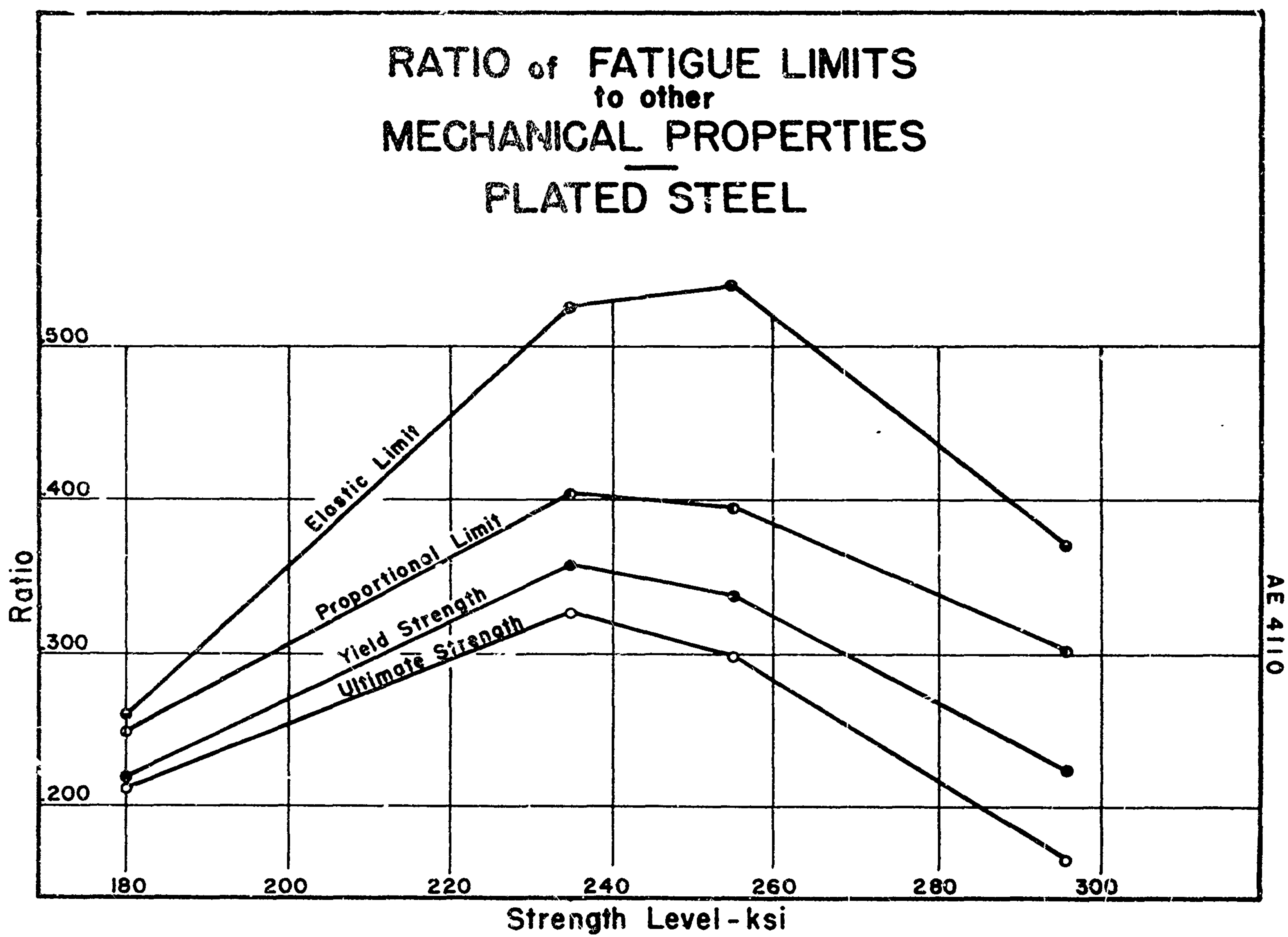

RATIO of FATIGUE LIMITS
to other
MECHANICAL PROPERTIES
PLATED STEEL
.500
.400
.300
.200
Ratio
Elastic Limit
Proportional Limit
Yield Strength
Ultimate Strength
180
200
220
240
260
280
300
Strength Level - ksi
AE 4110

Plate 10

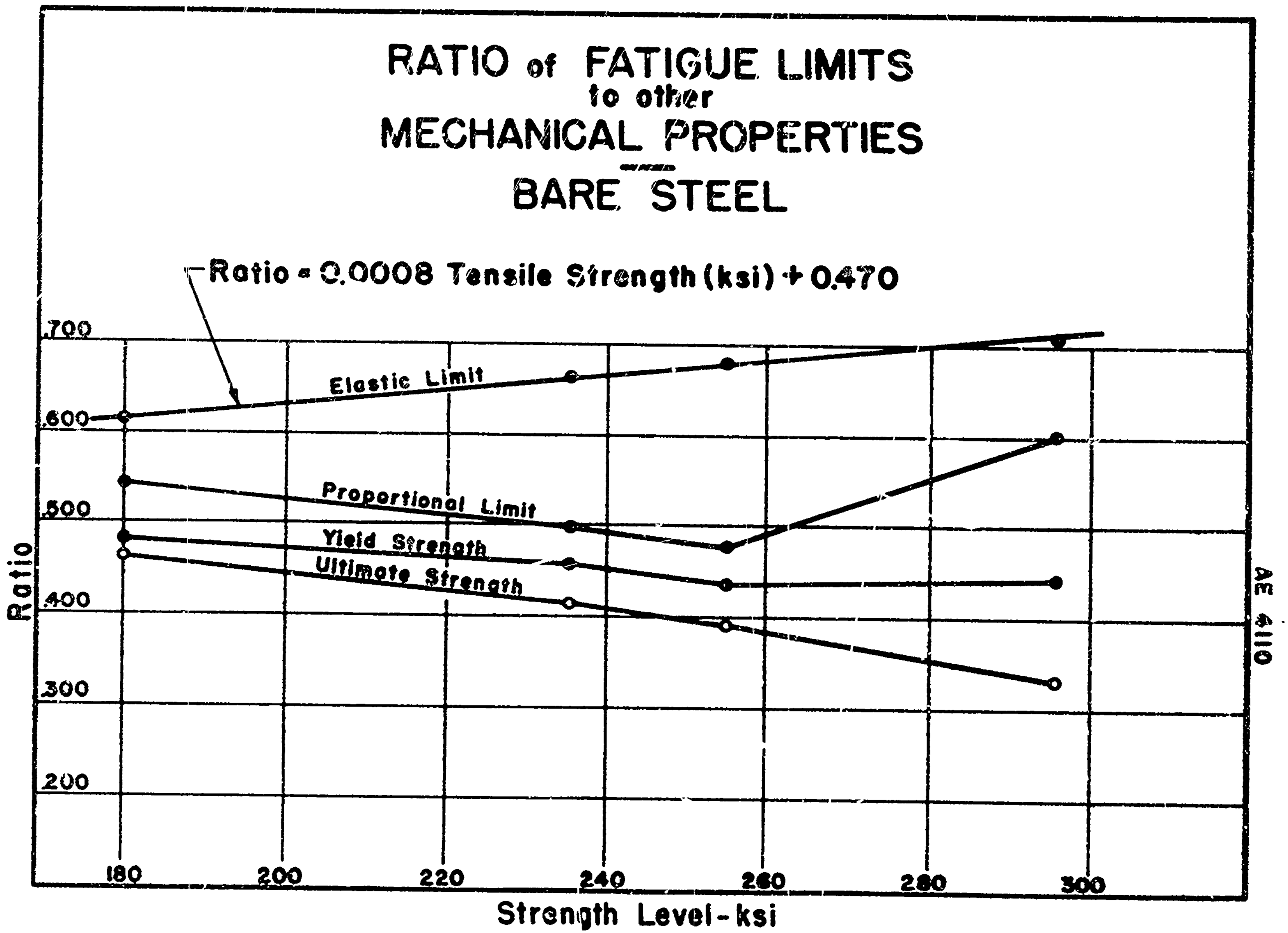

RATIO of FATIGUE LIMITS
to other
MECHANICAL PROPERTIES
BARE STEEL
Ratio = 0.0008 Tensile Strength (ksi) + 0.470
Elastic Limit
Proportional Limit
Yield Strength
Ultimate Strength
.700
.600
.500
.400
.300
.200
Ratio
180
200
220
240
260
280
300
Strength Level - ksi
AE 4110

Plate II

Fatigue Evaluation Results, 180 ksi Strength Level

Control		Plated		Plated and Baked	
Stress/psi	Cycles	Stress/psi	Cycles	Stress/psi	Cycles
120,000	41,000	120,000	11,000	120,000	17,000
112,000	65,000	110,000	21,000	110,000	45,000
105,000	134,000	80,000	52,000	70,000	101,000
97,000	161,000	65,000	106,000	65,000	208,000
90,000	571,000	50,000	224,000	62,000	374,000
87,000	778,000	40,000	403,000	61,000	229,000
85,000	757,000	39,000	246,000	60,000	35,126,000*
83,000	22,284,000*	38,000	18,010,000*	60,000	1,250,000
84,000	28,879,000*	38,000	27,976,000		

Shot-Peened		Shot-Peened and Plated		Shot-Peened, Plated and Baked	
Stress/psi	Cycles	Stress/psi	Cycles	Stress/psi	Cycles
120,000	54,000	120,000	27,000	120,000	47,000
110,000	141,000	105,000	93,000	110,000	93,000
100,000	668,000	95,000	277,000	105,000	275,000
95,000	570,000	90,000	284,000	100,000	439,000
93,000	790,000	85,000	347,000	97,000	983,000
92,000	620,000	83,000	654,000	96,000	2,567,000
91,000	27,000,000*	82,000	28,725,000*	95,000	22,000,000*

Summary of Fatigue Test Results

Condition	Fatigue Limit/psi
Basis Metal	84,000
Plated	38,000
Plated and Baked	59,000
Shot-Peened	91,000
Shot-Peened and Plated	82,000
Shot-Peened, Plated and Baked	95,000

APPENDIX 1
TABLE 1

*Indicates no failure

Fatigue Evaluation Results, 235 ksi Strength Level

Control		Plated		Plated and Baked	
Stress/psi	Cycles	Stress/psi	Cycles	Stress/psi	Cycles
140,000	39,000	140,000	18,000	140,000	20,000
120,000	80,000	120,000	32,000	120,000	42,000
110,000	88,000	100,000	82,000	110,000	52,000
105,000	210,000	90,000	89,000	100,000	96,000
100,000	195,000	80,000	158,000	90,000	170,000
100,000	224,000	78,000	183,000	85,000	399,000
99,000	20,147,000*	77,000	19,995,000*	80,000	234,000
99,000	457,000	77,000	326,000	80,000	610,000
98,000	38,864,000*	76,000	20,020,000*	79,000	25,632,000*
98,000	20,096,000*	76,000	26,661,000*	79,000	66,293,000*

Shot-Peened		Shot-Peened and Plated		Shot-Peened, Plated and Baked	
Stress/psi	Cycles	Stress/psi	Cycles	Stress/psi	Cycles
140,000	47,000	140,000	26,000	140,000	29,000
120,000	213,000	120,000	89,000	120,000	204,000
115,000	820,000	-----	----	-----	-----
110,000	1,316,000	110,000	163,000	110,000	1,677,000
105,000	3,824,000	105,000	676,000	105,000	7,141,000
103,000	1,383,000	104,000	948,000	104,000	5,921,000
102,000	4,917,000	103,000	329,000	103,000	22,929,000*
101,000	24,247,000*	102,000	65,688,000*		

Summary of Fatigue Test Results

Condition	Fatigue Limit/psi
Basis Metal	98,000
Plated	76,000
Plated and Baked	79,000
Shot-Peened	101,000
Shot-Peened and Plated	102,000
Shot-Peened, Plated and Baked	103,000

APPENDIX 1
TABLE 2

*Indicates no failure

Fatigue Evaluation Results, 255 ksi Strength Level

Control		Plated		Plated and Baked	
Stress/psi	Cycles	Stress/psi	Cycles	Stress/psi	Cycles
140,000	31,000	120,000	34,000	120,000	29,000
130,000	45,000	100,000	48,000	100,000	90,000
120,000	81,000	85,000	178,000	90,000	90,000
110,000	419,000	82,000	92,000	85,000	128,000
105,000	986,000	80,000	195,000	80,000	199,000
100,000	1,348,000	79,000	466,000	78,000	275,000
99,000	24,092,000*	78,000	20,841,000*	77,000	34,141,000*
99,000	734,000	78,000	1,176,000	77,000	206,000
98,000	31,181,000*	77,000	27,122,000*	76,000	29,874,000*
		77,000	22,162,000*	76,000	26,128,000*

Shot-Peened		Shot-Peened and Plated		Shot-Peened, Plated and Baked	
Stress/psi	Cycles	Stress/psi	Cycles	Stress/psi	Cycles
140,000	55,000	140,000	45,000	140,000	85,000
120,000	811,000	120,000	462,000	120,000	1,129,000
110,000	511,000	110,000	411,000	110,000	4,163,000
107,000	14,298,000	105,000	4,517,000	105,000	9,439,000
105,000	13,914,000	100,000	4,722,000	100,000	11,723,000
103,000	2,253,000	99,000	3,789,000	100,000	12,195,000
102,000	22,479,000*	98,000	2,472,000	99,000	25,150,000 *
		97,000	25,665,000*		

Summary of Fatigue Test Results

Condition	Fatigue Limit/psi
Basic Metal	98,000
Plated	77,000
Plated and Baked	76,000
Shot-peened	102,000
Shot-peened and Plated	97,000
Shot-peened, Plated and Baked	99,000

APPENDIX 1
TABLE 3

*Indicates no failure

Fatigue Evaluation Results, 295 ksi Strength Level

Control

Stress/psi	Cycles
140,000	49,000
135,000	123,000
130,000	190,000
125,000	145,000
115,000	126,000
110,000	341,000
105,000	766,000
100,000	906,000
98,000	13,850,000
97,000	28,432,000*
97,000	21,234,000*

Plated

Stress/psi	Cycles
97,000	29,[illegible]
90,000	39,000
80,000	83,000
60,000	180,000
50,000	265,00[illegible]
49,000	3,496,0[illegible]
48,000	20,000,[illegible]*
48,000	25,686,[illegible]0*

Plated and Baked

Stress/psi	Cycles
97,000	39,000
60,000	202,000
50,000	470,000
49,000	654,000
48,000	29,544,000*

Shot-Peened

Stress/psi	Cycles
155,000	114,000
145,000	199,000
135,000	397,000
110,000	3,273,000
105,000	5,727,000
100,000	8,785,000
[illegible]9,000	11,801,000
9[illegible],000	15,899,000
98,000	30,342,000*

Shot-Peened and Plated

Stress/psi	Cycles
140,000	66,000
120,000	321,000
110,000	333,000
100,000	10,113,000
95,000	3,029,000
92,000	2,070,000
91,000	18,132,000
90,000	25,705,000*
90,000	22,981,000*

Shot-Peened, Plated and Baked

Stress/psi	Cycles
140,000	128,000
120,000	325,000
110,000	1,431,000
108,000	8,233,000
106,000	5,498,000
105,000	4,158,000
102,000	12,160,000
100,000	33,000,000*

Machined

Stress/psi	Cycles
140,000	34,000
125,000	85,000
110,000	245,000
100,000	2,159,000
99,000	1,538,000
98,000	27,758,000*
98,000	21,597,000*

APPENDIX 1
TABLE 4
(Page 1 of 2 Pages)

*Indicates no failure

295 ksi Strength Level (Continued)

Summary of Fatigue Test Results

Condition	Fatigue Limit/psi
Basis Metal - Machined	98,000
Basis Metal - Ground (Control)	97,000
Plated	48,000
Plated and Baked	48,000
Shot-Peened	98,000
Shot-Peened and Plated	90,000
Shot-Peened, Plated and Baked	100,000

Fatigue Evaluation Results, 295 ksi Strength Level
Peening After Chrome Plating

Plated and Shot-Peened		Plated, Shot-Peened and Baked	
Stress/psi	Cycles	Stress/psi	Cycles
140,000	171,000	140,000	179,000
120,000	433,000	120,000	1,862,000
110,000	2,082,000	110,000	4,321,000
105,000	5,396,000	107,000	3,875,000
104,000	2,707,000	106,000	6,674,000
103,000	1,879,000	105,000	3,222,000
102,000	17,998,000	105,000	6,447,000
101,000	8,427,000	104,000	17,470,000
100,000	15,869,000	103,000	9,978,000
99,000	20,853,000*	102,000	25,788,000*

Summary of Fatigue Test Results

Condition	Fatigue Limit/psi
Base Metal	67,000
Plated	48,000
Plated and Baked	48,000
Shot-Peened	98,000
Shot-Peened and Plated	90,000
Shot-Peened, Plated and Baked	100,000
Plated and Shot-Peened	99,000
Plated, Shot-Peened and Baked	102,000

* Indicates no failure

Results of Static Strength Tests - All Strength Levels

180 ksi Strength Level

Bare Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	181,100	173,500	150,000	137,500
	182,800	173,500	157,500	135,000
	181,500	173,500	155,000	137,500
Avg.	181,800	173,500	154,167	136,667

Plated Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	180,500	175,000	157,500	147,500
	181,750	175,000	150,000	147,500
	180,750	175,000	157,500	147,500
Avg.	181,000	175,000	155,000	147,500

235 ksi Strength Level

Bare Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	230,740	212,090	188,970	150,680
	239,690	218,010	201,400	145,330
	237,600	216,320	201,400	146,700
Avg.	236,010	215,473	197,257	147,570

Plated Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	239,390	218,360	199,080	141,840
	231,320	211,510	178,320	145,620
	231,240	210,550	188,210	146,700
Avg.	233,983	213,457	188,537	144,720

255 ksi Strength Level

Bare Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	250,340	226,450	209,030	146,800
	251,830	224,960	209,030	145,450
	251,340	223,960	198,080	140,350
Avg.	251,170	225,123	205,380	144,200

Plated Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	261,530	231,810	193,180	146,000
	251,630	225,370	198,130	142,100
	261,530	232,800	198,130	140,690
Avg.	258,230	229,993	196,480	142,930

295 ksi Strength Level

Bare Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	305,590	223,960	159,260	139,350
	283,950	221,300	166,730	142,130
	300,610	218,900	158,260	130,520
Avg.	296,717	221,387	161,417	137,333

Plated Steel

	Ultimate Strength/psi	Yield Strength/psi	Proportional Limit/psi	Elastic Limit/psi
	285,420	217,880	162,820	126,200
	290,600	215,850	157,880	130,740
	302,400	219,060	157,880	133,200
Avg.	292,807	217,597	159,527	130,046

Evaluation of Corrosion Resistance

Treatment	Specimen No.	Hours of Salt Spray 1	3	4	6	23	25	27	43	51	115	139
1. Plated and Peened	49	1	1	1	1	1	1	1	1	1	1	2
	49	1	1	1	1	1	1	1	1	1	1	1
	50	1	1	1	1	1	1	1	1	1	2	2
	50	1	1	1	1	1	1	1	1	1	1	1
2. Plated, Peened and Baked	59	1	1	1	1	1	1	1	1	1	1	1
	59	1	1	1	1	1	1	1	1	1	1	2
	60	1	1	1	1	1	1	1	1	1	1	1
	60	1	1	1	1	1	1	1	1	1	3	3
3. Plated and Baked	73	1	1	1	1	1	1	1	1	1	1	1
	73	1	1	1	1	2	2	2	2	2	2	2
	74	1	1	1	1	1	1	1	1	1	1	1
	74	1	1	1	1	1	1	1	1	1	1	1
4. Plated only	69	1	1	1	2	3	3	3	3	3	3	3
	69	1	1	1	1	2	2	2	2	2	2	2
	70	1	1	1	1	2	3	3	3	3	3	3
	70	1	1	1	1	2	2	2	2	2	2	2
5. Peened, Plated and Baked	X1	1	1	1	1	2	2	2	2	2	2	2
	X1	3	3	3	3	3	3	3	3	3	3	3
	X2	3	3	3	3	3	3	3	3	3	4	4
	X2	3	3	3	3	3	3	3	3	3	4	4
6. Peened and Plated	105	3	3	3	3	3	3	3	3	3	4	4
	105	3	3	3	3	3	3	3	3	3	4	4
	110	3	3	3	3	3	3	3	3	3	4	4
	110	3	3	3	3	3	3	3	3	3	4	4

Rating System

Code	Percentage of the surface pitted or corroded
1	0 to 20
2	20 to 40
3	40 to 60
4	69 to 90

APPENDIX 1
TABLE 7